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Eric E. Bloemhof, Ben R. Oppenheimer, Richard G. Dekany, Mitchell Troy, Thomas L. Hayward, Bernhard Rainer Brandl, "Studies of Herbig-Haro objects with the Palomar adaptive optics system," Proc. SPIE 4007, Adaptive Optical Systems Technology, (7 July 2000); doi: 10.1117/12.390380

Event: Astronomical Telescopes and Instrumentation, 2000, Munich, Germany

Studies of Herbig-Haro Objects with the Palomar Adaptive Optics System

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ABSTRACT

Herbig-Haro objects are bright optical emission-line sources associated with tightly collimated jets ejected from pre-main-sequence stars. Only a few hundred are known. In optical images, they appear to be dense knots of material at the outer ends of the jets, and often exhibit streaming wake morphologies suggestive of bow shocks. Their optical spectra show characteristics of high-velocity shocks, with line-widths typically 100 km/s. HH objects often occur in pairs consistent with the bipolar morphology of outflows from YSOs; when radio maps of NH3 are made, high-density central regions consistent with collimating disks are seen. HH objects also often appear in a series along a jet, presumably where the jet undergoes a particularly energetic interaction with the ambient medium. Adaptively-corrected near-infrared studies of HH objects can reveal much about their workings at fine spatial scales. Narrow-band NIR filters sensitive to transitions of molecular hydrogen and other selected species are excellent tracers of shock excitation, and many HH objects have been observed to show complex structure in these lines down to the arc second level. By pushing to higher spatial resolution with adaptive optics, much more detailed information about the nature of the shock fronts may be obtained. In this paper we describe our first observations of HH objects with the AO system on the Palomar 200-inch telescope.

Keywords: adaptive optics, star formation, shocks

1. INTRODUCTION

Star formation is fundamentally the process of collapsing clouds of diffuse interstellar material from parsec scales to solar-system (and smaller) scales. Yet, as has become clear from observations and detailed theoretical models over the last few years, the collapse phase is accompanied by extremely energetic outflows of material as well, driving material into the surrounding interstellar medium at hundreds of kilometers per second. In hindsight, it is clear that outflows are necessary to help dissipate the angular momentum that is associated with the large parent cloud and is concentrated during collapse. Protostellar outflows are characteristically bipolar, and launched by magnetohydrodynamic mechanisms initially along the angular momentum axes of the rotating accretion disks that build up around protostars. Molecular outflows are primarily seen in CO emission at radio wavelengths, while tracers of the ionized gas component are observed at radio, optical, and infrared wavelengths.

Protostellar outflows eventually travel far enough from their sources to be directly visible. Their study can potentially provide information about the interstellar medium into which they are ejected, and they also may retain clues to events that occurred in the center of the star formation engine that launched the flow. Outflows exhibit complex morphologies in optical and near-infrared images, often tracing meandering paths and showing signposts of energetic line emission at positions where the flow might be colliding with particularly dense ambient material. Radio continuum observations[1] at high spatial resolution may delineate the ionized component of outflows; observations[2] in lines from species such as NH_3, tracing high-density molecular gas, can reveal complementary collimating structures near the presumed origins of some flows. These radio studies may be carried out with interferometers, in which case sub-arcsecond spatial resolution may be achieved.

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In *Adaptive Optical Systems Technology*, Peter L. Wizinowich, Editor, Proceedings of SPIE Vol. 4007 (2000) • 0277-786X/00/$15.00

There have been exciting demonstrations of large-scale coherent structure in protostellar outflows; linear alignments of Herbig-Haro knots along streamers of fainter emission delineating the outflow can be seen extending over parsec scales, in some cases[3]. An unusually explosive outflow in Orion[4] exhibits multiple streamers with entrained Herbig-Haro knots from each side of the OMC-1 core; in mosaiced infrared images of the H_2 2.122-μm and [Fe II] 1.644-μm shock-excited lines, these streamers extend for arcminutes.

Optical and infrared studies of the sub-arc second morphology of individual Herbig-Haro knots have not been technologically possible in the past, although complex structure down to the limits of available resolution has been seen. Achieving the highest spatial resolution possible is of great importance, both for probing protostellar outflows to their innermost scales, and for understanding the working of Herbig-Haro knots themselves. Quite generally, Herbig-Haro objects and their associated outflows, as they interact with the interstellar medium, provide an instructive laboratory for the study of astrophysical hydrodynamics and turbulence.

2. SHOCK EXCITATION TRACERS

A particularly useful diagnostic of protostellar outflows is the presence of shocks, as revealed by emission lines that can only be produced in conditions of high excitation. The location of this emission may reveal the "working surfaces" at which a high-velocity outflow collides with stationary ambient material. Suitable high-excitation lines can be found at visible wavelengths and in the near-infrared bands accessible to the PALAO adaptive optics system; these will be discussed below.

The basic nature of Herbig-Haro objects, still not clear, can be addressed by systematic observations of shock morphology. Two distinctly different interpretations of Herbig-Haro objects are most popular. In the "interstellar bullet" model[5] the Herbig-Haro object is a dense clump of gas ejected with high velocity into the ambient molecular cloud medium. In the "shocked cloudlet" model[6], Herbig-Haro objects are stationary knots of material that are hit by the collimated supersonic wind, or jet, from a young stellar object (YSO). These two models would predict substantially different patterns of shock excitation. In the interstellar bullet model, the highest excitation should occur on the opposite side of the Herbig-Haro object from the jet; in the shocked cloudlet model, the highest excitation should occur on the same side as the jet.

Many YSO jets show sinuous structure, and it is not always clear whether an otherwise steady outflow is encountering inhomogeneities in the medium through which it passes, or whether the jet itself is undergoing time variations in strength and/or direction (e.g. "precessing"). If outflows show complex trajectories in their innermost regions, before travelling far through the surrounding medium, it is much more likely that the variations are intrinsic to the source, i.e., to the protostellar outflow mechanism; this would have profound implications. In this study, mapping of shock excitation is a particularly valuable tool for determining whether a bend in the outflow marks a channeling by the ambient medium or a reorientation of the source. As with sinuous structure, departures from bipolar symmetry would have profound implications if found by high spatial resolution imaging in the innermost regions of the outflow, before extensive interaction with the surrounding medium.

2.1. Optical Forbidden Lines

The classical detection of shock excitation in protostellar outflows has been through observations of Hα at 6563 Å, and of a number of optical forbidden lines. Many optical studies have employed narrow-band imaging in [SII] at 6717 Å and 6731 Å, but emission is generally also seen in [OI] (6300 and 6363 Å), [NII] (6548 and 6584 Å), [OIII] (5007 Å), and other species. Owing to the different excitation conditions required to produce these transitions, their morphologies vary somewhat as they delineate different structures: generally, SII traces the core of the outflow, while Hα appears more nebulous and originates in the outer part of the outflow.

2.2. Near-Infrared Shock Tracers

Traditional near-infrared array imaging of shocked gas has particularly exploited two lines of successively higher excitation: the H_2 ($v = 1 - 0$) line at 2.122 μm, and the [Fe II] line at 1.644 μm.

At the time of our observations, a sufficiently high quality filter at the traditional molecular hydrogen line was not available, so we observed instead the H_2 (2-1) line at 2.248 um, for which a filter exists as part of PHARO's standard complement. Also available to us was a filter at the [FeII] line wavelength at 1.644 um.

3. OBSERVATIONS WITH PALOMAR ADAPTIVE OPTICS

3.1. The PALAO Instrument

PALAO, the Palomar adaptive optics system for the 200-inch telescope, is based on a 349-actuator PMN deformable mirror and a visible-light Shack-Hartmann wavefront sensor that places a 16x16 array of subapertures across the pupil. Centroids are measured by a low-noise 64x64 CCD capable of readout rates as high as 500 Hz. Overall tip-tilt is corrected by a separate fast-steering mirror, with a closed-loop bandwidth of $\sim$5 Hz. A comprehensive description of the instrument's current status may be found elsewhere in this volume,[7] and some aspects of its design and construction have also been published.[8] PALAO feeds a specially-designed near-infrared (JHK) science camera called PHARO (Palomar High Angular Resolution Observer).[9] Although designed with sufficient flexibility to accommodate a laser beacon, PALAO is now and for the foreseeable future a natural guide star system. PALAO first achieved high-order correction at the telescope in December, 1998, and has been used productively during the 1999 observing season for a variety of scientific projects. Initial results have been most encouraging, and are discussed elsewhere in this volume.[10,11]

3.2. Observing Strategies

Apart from engineering studies specifically intended to test flexure and performance under conditions of high atmospheric turbulence, we generally gather adaptive optics data as close as possible to the zenith. In our first observing season, we generally used short integration times, perhaps a few minutes, with our science exposures. The standard dark, flat, and sky calibration frames of infrared astronomy were obtained, as discussed in more detail in the next section.

3.3. Data Reduction

All of the PALAO images presented in this paper were reduced by the standard techniques of astronomical near-infrared array imaging. Dead pixels were detected in flat-field exposures, usually taken on the sky at sunrise or sunset (or, if sky flats were not taken, on an illuminated region of the dome); hot pixels were detected in dark exposures; these bad pixels were removed by an iterative algorithm that replaces them with an average of contiguous good pixels. For good pixels, dark exposures provide pixel offsets, and flats, with exposure parameters chosen to match their corresponding observations, provide pixel responsivity calibration. Sky exposures on a nominally empty field allow subtracting out the uniform component of the infrared emission of the sky, or the telescope may be dithered between exposures on the science object to accomplish an equivalent sky measurement (and avoid bad regions on the CCD). Data reduction was greatly aided by a standard package of IDL routines called "AOred", written by Jason Marshall and Mitchell Troy of JPL, and made available to the community of PALAO users.

4. HERBIG-HARO OBJECT HH 189E

4.1. Optical Vicinity

HH 189E is located in a fairly rich region region of apparently intersecting protostellar flows in Cepheus. HH 189E lies near the end of a prominent flow punctuated by HH 189A, B, C and D, and generally illuminated in optical shock-emission lines (see Figure 1, reproduced from Alten *et al.*[12]). The linear structure of HH 189 is crossed, at least in two-dimensional projection, by HH 364, also generally linear; both are dotted with bright emission-line knots. Complexes HH 373 and HH 374 are nearby, with geometries that hint at a relation among the various structures.

We wished to observe HH 189E to determine whether this is the site of a sharp directional change, with the flow then continuing to possible HH objects NW of the bright (AO guide) star (Figure 1), or whether this is the terminal shock of the very large flow originating far to the south.

4.2. Guide Star

HH 189E is fortuitously located roughly 0.5 arcmin from a bright (9.1 magnitude) star visible at upper left in Figure 1, making it amenable to study with natural-guide-star adaptive optics. The guide star, almost due north of the region of interest, is presumably unrelated to the linear Herbig-Haro complex. Under reasonably good seeing conditions, a guide star of 9.1 magnitudes at V is adequate to provide a relatively strong high-order lock for the PALAO system: locks have so far been achieved with guide stars as faint as about 13 magnitudes, although of less than highest quality.

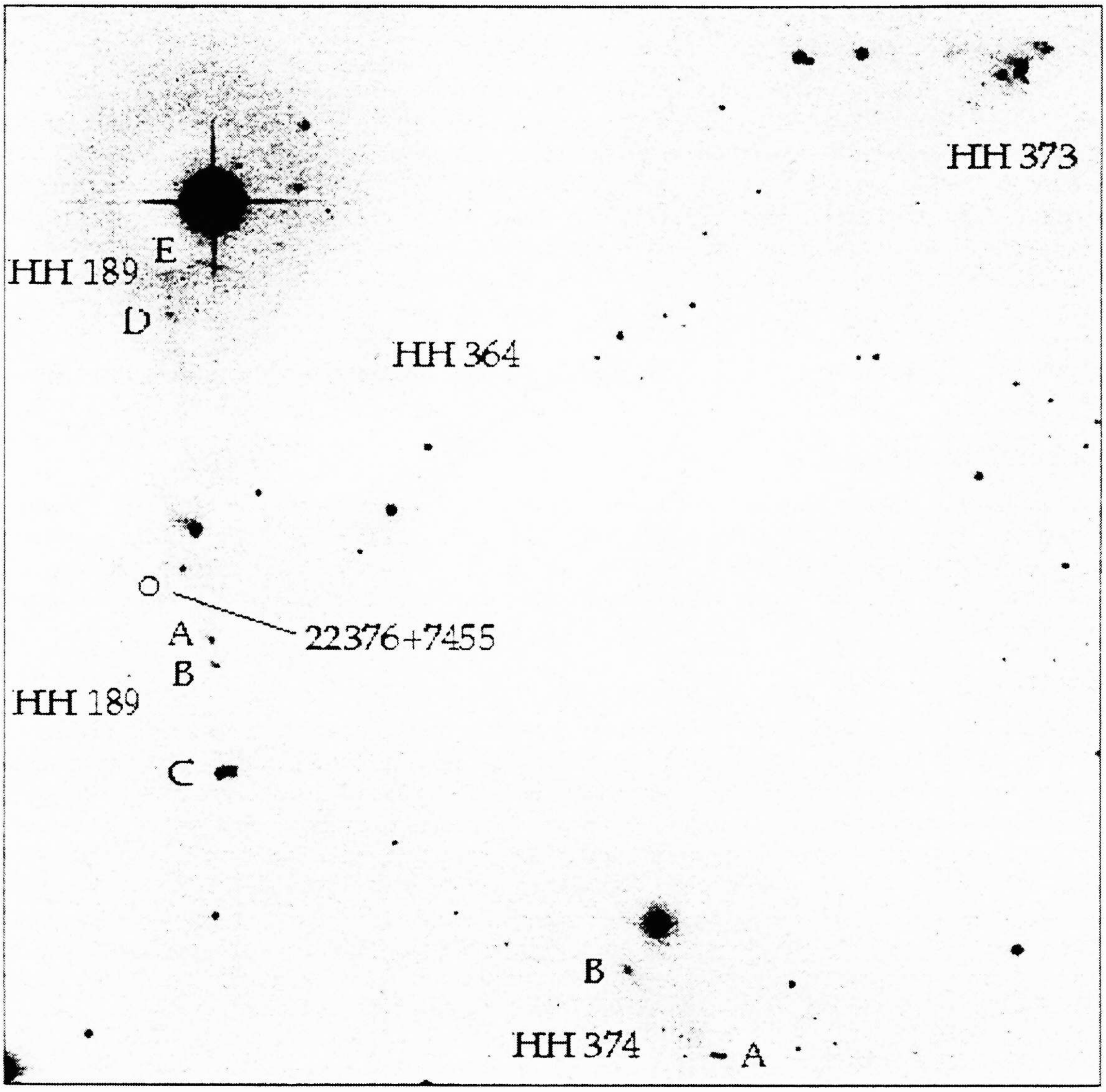

Figure 1. Vicinity of HH 189 imaged in optical shock tracers, reproduced from Alten *et al.*[12]. North is up and east is to the left; the field of view measures roughly 8 arcminutes on a side. HH 189E is located about 0.5 arcminutes south of the bright star (V = 9.1^m) at upper left that serves as the adaptive optic guide star.

It is generally expected that the limited isoplanatic patch in the near-infrared will restrict adaptive optics observations to regions of sky within perhaps 20 arc seconds of the guide star. Experience at Palomar shows that anisoplanatic effects (e.g., an elliptical point-spread function whose long axis points back to the guide star) are indeed seen with such separations. However, substantial correction is still achieved at these scales and beyond.

4.3. PALAO Observations

Our observations of HH 189 were made on 1999 August 28 under conditions of relatively good uncorrected seeing. We used a plate scale giving 40 milliarcsecond pixels, and roughly a 40 arcsecond $\times$ 40 arcsecond field of view on our 1024x1024 science CCD. A high-quality lock was obtained, and several exploratory images south of the guide star were made in the shocked-emission filter, H_2, and in the broad-band standard J, H, and K filters. No conspicuous emission was seen, but only a very short total integration time (a few minutes) was invested at any one position.

4.4. PALAO Static-Correction Mode

To follow the chain of Herbig-Haro objects seen in the optical, we obtained images further south than the acquisition range of our wavefront sensor. We did this in a "static-correction" mode, in which the adaptive-optic loop was unlocked, but a static wavefront correction from a long time-average previously obtained on a guide star is applied to the deformable mirror. This mode achieves a not-insignificant improvement in telescope PSF by fixing the substantial aberrations of the primary mirror; at Palomar, those aberrations are known to lead to noticeable PSF structure that varies with pointing over the sky, and exhibits complicated hysteretic behavior.

While imaging the neighborhood of the fairly bright star just northwest of HH 374B in Figure 1, we tested another intermediate mode in which only the tip-tilt control loop is closed. This requires a substantially fainter guide star than does the full high-order lock. A successful tip/tilt lock was achieved, but little conspicuous emission was seen in two short (30-second) exploratory integrations.

5. HERBIG-HARO OBJECT HH 45

5.1. Optical Vicinity

In Figure 2 we present an Hα (6563 Å) image of the immediate vicinity of HH 45, reproduced from Reipurth[13].

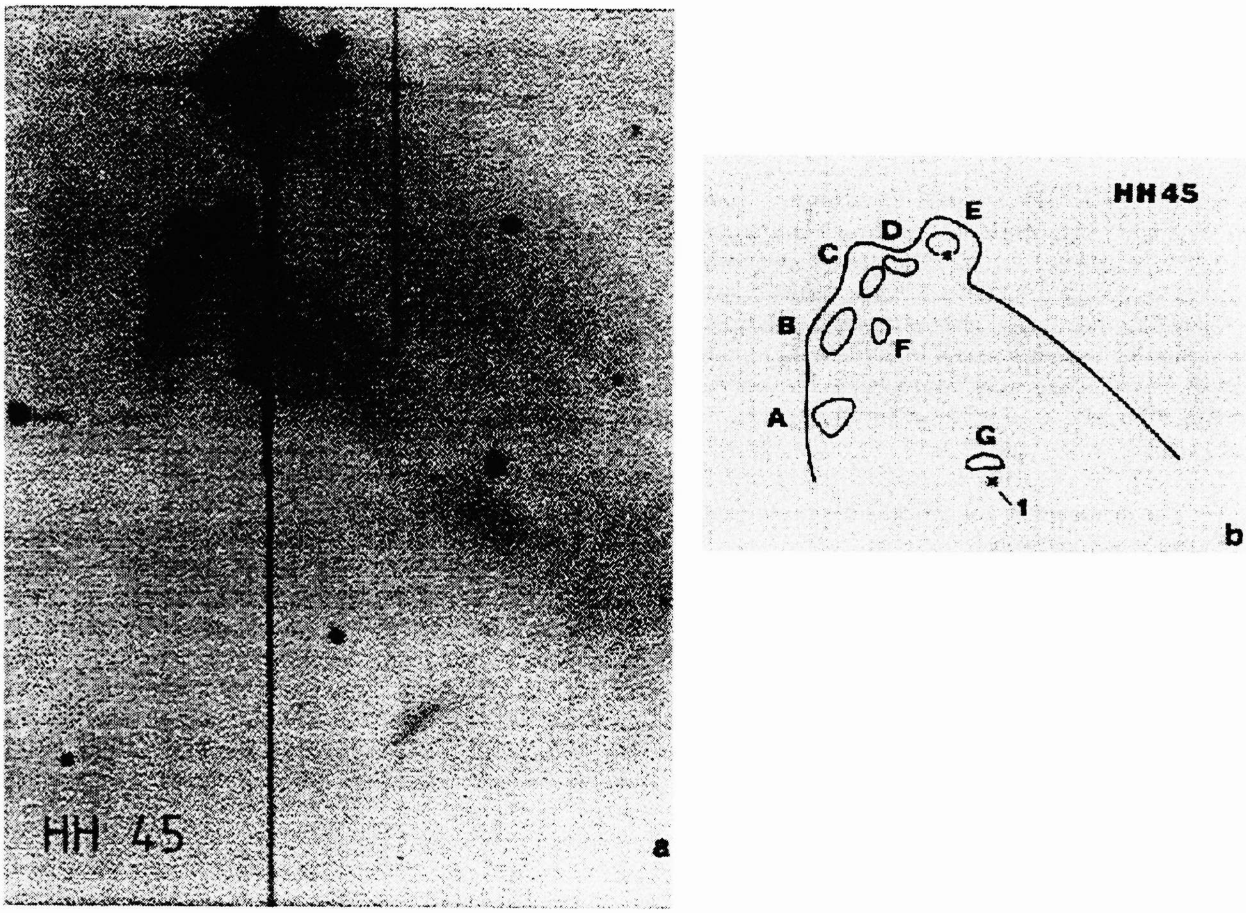

Figure 2. a) Vicinity of HH 45 imaged in Hα 6563 Å, reproduced from Reipurth[13]. North is up and east is to the left; the field of view measures roughly 2 by 5.5 arcminutes. HH 45 is the cometary shock front located about 0.6 arcminutes south-southeast of the bright star ($V = 7.3^m$) at top center that serves as the adaptive optic guide star. b) Schematic of HH 45 used to assign identifications (also from Reipurth[13]). The asterisk near source G denotes a positional reference star ("Star 1").

The field is located in Orion, in a region rich with protostellar activity and with Herbig-Haro objects. The morphology suggests a bow shock along the arc formed by HH 45A-E, but with a great deal of complex substructure. The source designated "Star 1" is about 55 arcseconds, almost due south, from the bright star at top center of Figure 2, and partially obscured in that image by a diffraction spike. HH 45 was observed previously with a near-infrared camera and filters sensitive to shocked emission (H_2 1-0 and [FeII]) at the Palomar 60" telescope. Those images show tentative indications of shocked emission from the cometary front and from the compact nebulosity downstream from that front (directly south of the guide star). However, the dramatically higher angular resolution of the Palomar adaptive optics system is potentially of great value to understanding this system.

5.2. Guide Star

HH 45 is located about 0.6 arcmin from an apparently unrelated star of 7.3 magnitudes in the visible band, seen at top center in Figure 2, suitable for a very strong high-order lock with the Palomar adaptive optics system. The distance from the natural guide star is near the generally-accepted limits for the isoplanatic scale in the near-infrared.

5.3. PALAO Observations

Figure 3 shows two images obtained in September, 1999, of a 40 arcsec $\times$ 40 arcsec region extending south from the guide star; HH 45 lies in the southern third of this field. The dark spots at the left and upper edges are artifacts due to stars in the subtracted off-source field used to monitor sky emission, and a ghost due to a stray reflection in the adaptive optics system's dichroic is visible as an out-of-focus image $\sim$ 16 arcseconds west-southwest of the guide star at top center. At the bottom of the field, somewhat east of center, is an apparently stellar source; just north of that is a faint nebulosity that appears non-stellar. There also appears to be emission near the southern boundaries in Figure 3, to the east of the stellar source, that is apparently real; this is a clean, artifact-free edge of the chip.

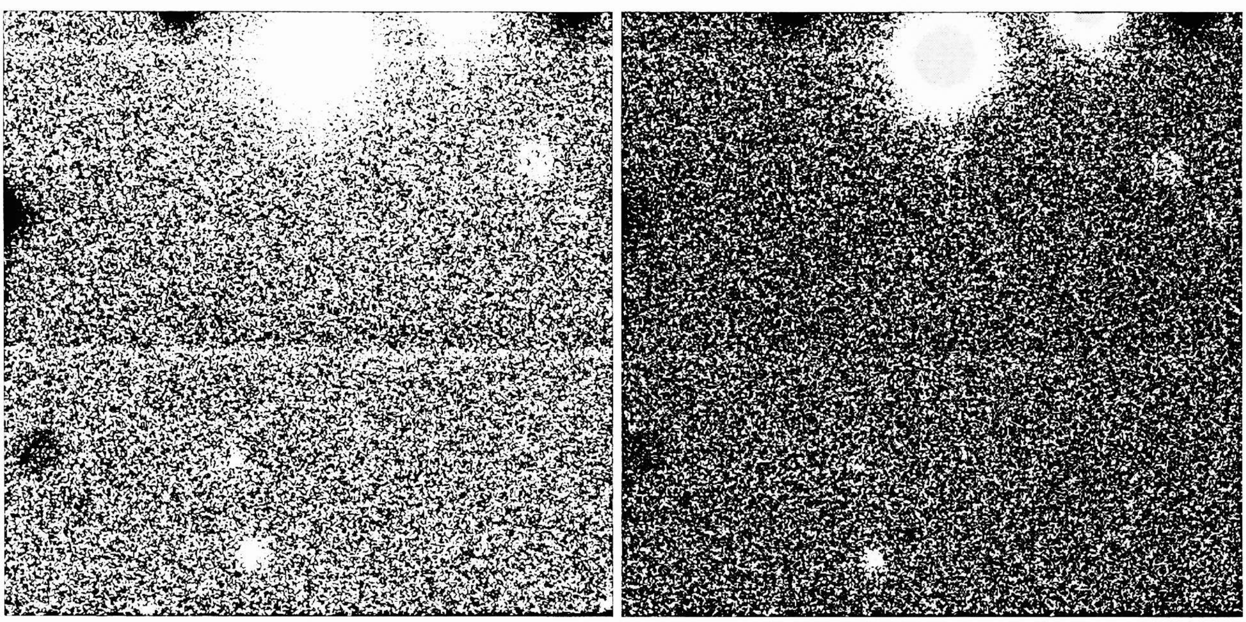

Figure 3. PALAO images of the HH 45 region: (left) Br-γ filter; (right) H_2 filter; both are 300 second exposures. North is up and east is to the left; the field of view measures 40 arcseconds on a side. The saturated spot at top center is the guide star from Figure 2. The Br-γ filter traces general emission from ionized gas, while the H_2 filter should be more particularly sensitive to high-excitation ("shocked") emission.

Figure 4 shows another image of the region near HH 45, obtained in August, 1999. The field is about half an arcminute south of the field depicted in Figure 3. The stellar source and the nebulosity just north of it are again visible, near the top of Figure 4, and two more apparently stellar sources have entered the field of view at the south. (The faint nebulous source at top center is not merely an after-image of the guide star, which was off-chip for the two preceding exposures and was positioned elsewhere on the chip before that).

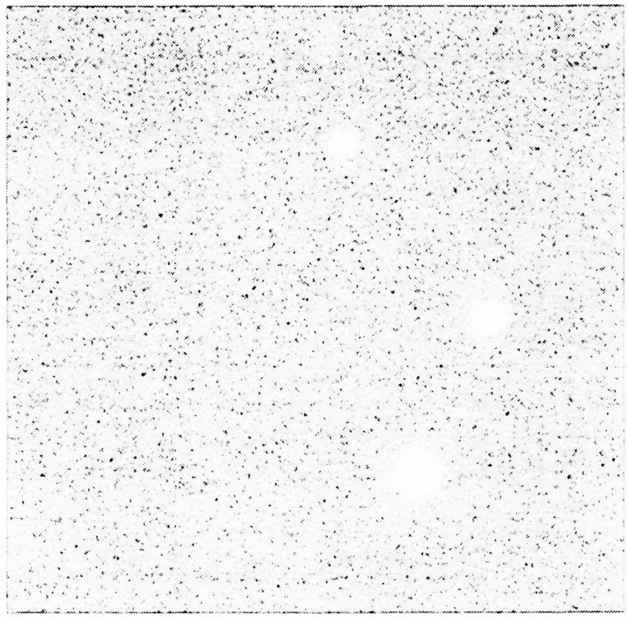

Figure 4. PALAO image of the HH 45 region, positioned roughly 30 arcsec south of the images in Figure 3; exposure time is 300 seconds. Again, north is up and east is to the left; the field of view measures 40 arcseconds on a side. The brightest star, near the bottom of this K-band image, is the object designated "Star 1" by Reipurth[13]. The nebulosity at top center is the same source seen in both filters at bottom center in Figure 3.

Careful comparison with the optical images shows that the brightest of the stellar sources in Figure 4, near the southern edge of the field, is Reipurth's "Star 1" labelled in Figure 2b. Also, the faint nebulous source at the top center of Figure 4, or bottom center of Figure 3, is at the position of the bright knot identified by Reipurth as HH 45E. Reipurth also notes a star very close to this position, though our source gives an impression of non-stellar morphology. We note that the source on the southern edge of Figure 3, in both Br-γ and H_2, would lie roughly on Reipurth's cometary shock front; this source is not apparent in the K-band filter taken a month earlier (Figure 4). There are one or two additional regions of faint emission that appear to be fairly secure as astrophysical detections, and correlate with the shock structures seen in optical photographs; they are however difficult to display in these low-SNR short-exposure images.

In a cursory, qualitative assessment of these images, we have noted in particular the non-stellar appearance of the faint emission at the position of HH 45E that shows up in our Br-γ, H_2, and J-band images. This source seems proportionately rather bright in H_2, the filter sensitive to the highest excitation emission due to shocks. And the source appears to be positioned at the leading edge of the apparent bow shock, although it is not clear why it should show up more prominently than the other compact visible-light knots along the front. More quantitative conclusions must await more detailed analyses of our images; in particular, we must make sure that each source of emission we see is indeed associated with a shock front and not simply generated by a nearby star.

6. FUTURE PROSPECTS

The observations presented here constitute a quick look at a small sample of Herbig-Haro objects, with total integration times of just a few minutes. In addition to detections in HH 45 that may prove to be scientifically interesting, they have demonstrated technical feasibility in a number of areas.

The guide-star acquisition system of PALAO was shown to be capable of targeting a guide star far ($\sim$ 30 arcseconds and more) from the science field center. Moreover, as these and other PALAO observations have shown, the isoplanatic region is somewhat larger than anticipated, making the quality of the correction with such distant guide stars fairly good. Point-spread functions of perfect circular symmetry may in any case not be necessary for answering the scientific questions of interest.

6.1. Suitable HH Objects

Our experiences with HH 189E and HH 45 provided a useful exercise that should help to shape tactics for future observations of Herbig-Haro objects. Of course, a key constraint for a natural guide star system such as PALAO is the proximity of a sufficiently bright star, although future technical improvements may ease the magnitude limitations somewhat.

Being associated with current or recent star formation, Herbig-Haro objects are often located in regions of high general extinction. The protostar itself, in particular, is usually very heavily obscured for sources at this evolutionary stage, and essentially invisible at optical wavelengths. Infrared studies of shock tracers are all the more appropriate in these environments, and a future-generation infrared wavefront sensor contemplated for PALAO would be particularly helpful in making best use of nearby guide stars.

With current technology, there remain a few candidate Herbig-Haro objects amenable to study with the PALAO high-order, natural-guide-star adaptive optics system. It is clear that longer integration times will be necessary to make images with good dynamic range, given the very small size of our corrected pixels. However, the prospect of gaining detailed images of the shock structure of these objects on tenth-arcsecond scales should make those integration times worthwhile.

ACKNOWLEDGMENTS

We thank the staff of Palomar Observatory for their extensive and capable efforts in support of the PALAO adaptive optics system.

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